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Numerical study of extinction of visible and infrared radiation transformed by preferentially oriented plate crystals

Olga Shefer

Institute of Cybernetics, Tomsk Polytechnic University, Sovetskya str., 84/3, Tomsk 634004, Russia

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ABSTRACT

Extinction properties of an ensemble of semi-transparent plate crystals in preferred orientation are studied at wavelengths of visible and infrared ranges using the physical optics method. The work illustrates some calculations of the differential scattering coefficient in the near-forward and the exact forward directions. The features of energy and polarization characteristics of directly transmitted radiation through a set of particles are discussed, as depended on parameters of medium and the incident radiation. It is shown that the effect of polarization on extinction by large plates at certain combination of microphysical parameters of medium and the wavelength can be pronounced even for clean ice. By increasing the real part of complex refractive index, the polarized effect can be increased a few times. It is illustrated as an influence of flutter of plates on the considered characteristics.

1. Introduction

A determination of the extinction of the optical radiation for a polydisperse medium is related to a solution of many problems, in particular, such as studying of the atmosphere by the optical methods (e.g., the passive sensing and the laser sensing), studying of the optical characteristics of an individual crystal, and analyzing of the propagation of radiation in a medium (optical system). The extinction of the radiation by ensembles of arbitrarily shaped and sized particles with various optical and dynamic properties plays an important role in the atmospheric optics, the theory of the radiative transfer, and the determination of the thermal balance of the atmosphere [1–7]. Study of the optical characteristics of cirrus in the visible and infrared regions is a relevant problem. The optical crystal properties of polluted Earth's atmosphere or atmosphere of other planets can substantially differ from the optical properties of clean ice [4,8]. The problem of light scattering and extinction for chaotically oriented particles is widely presented in the scientific literature [1–4]. However, in the case of preferentially oriented crystals and especially for IR spectral region, it is poorly studied. Preferentially oriented crystals can change not only the energy characteristics of the incident radiation as it passes through the particles but also its state of polarization. For a full description of these characteristics, the scattering matrix and the extinction matrix (EM) are usually considered [1,2].

Among all large particles (sizes of a particle are much more than the wavelength), plate crystals distinctly stand out [9–13]. For a plate crystal, the extinction efficiency factor may take values from the widest interval such as from 0 to 4 (without the edge effect contribution). A numerical model of an individual large plate crystal was considered in our paper [12]. This model can be used to calculate the elements of the extinction matrix and the scattering matrix in the forward hemisphere for arbitrary locations of a source, a plate, and a receiver. We say that the forward hemisphere is the part of the sphere such that it is bounded by the plate base and also it contains the rays scattered in the forward direction. In the present paper we further extend the study that is represented in [12].

E-mail address: shefer-ol@mail.ru

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The numerical model [12] was developed by a hybrid method as a combination of the geometric optics method and the physical optics method. We employed the beam-spitting technique to simulate a propagation of each beam within the crystal and after the interaction with the crystal [13,14]. This technique considers all refracted rays as beams of parallel rays, which passed through a crystal or reflected from its faces. For each beam with different orders of reflection from plate faces, the phase shifts of wave are defined taking into account the plate thickness, the incident wave direction, the incident radiation wavelength, and the complex refractive index [12,13]. It should be outlined that we took into account the imaginary part of the refractive index; this is especially important for infrared wavelengths. So, the amplitude variation of the electric field over a beam cross section is considered. By determining of characteristics of the near-field we used Snell's law and the Fresnel transmission and reflectance coefficients for the perpendicular and parallel components of a plane wave. Then we applied a number of key approaches to determine the transformed field. We took into account the commensurability of the diffracted and refracted fields of beams passing through the particle [12,13,15]. A wave that passed through a crystal has constant phase in the cross section of the parallel rays beam. A common approach for determining the diffracted and refracted fields allows to sum them coherently; then the resultant field is well defined from near-field zone to far-field zone. To recalculate the field from the near-field zone to the far-field zone, we use the Fraunhofer integral.

Note that this hybrid method does not consider a possible edge effect. The larger the crystal dimensions, the better the method of physical optics describes the scattering of the electromagnetic field on a polyhedron. In work [16], on the basis of the well-known energy relationship as "extinction=scattering+absorption", we indicated the applicability limits of this method to problems of the light scattering on plate crystals. We obtained the following estimations: the calculation error for the optical characteristics is less than 10% when $a>1.6\lambda$ (where a is the radius of the plate, and λ is the incident radiation wavelength), less than 5% when $a>3.2\lambda$, less than 2% when $a>8.8\lambda$, and less than 1% when $a>19.1\lambda$. If the beam cross section is much more than its edge area, then the error of the method, ignoring the edge effect, vanished.

The method of physical optics for calculating optical characteristics is approximate, but it is sufficiently efficient for large particles. For a single plate, at small size parameter (from a few units to several tens), the edge component in extinction is especially pronounced [17]. For the large oriented particles, the characteristics of the field scattered in the near-forward direction depend primarily on the refractive field and diffraction field, and the edge effect is some amendment to the definition of transformed field. Going to the integral values (in particular, going from the cross-section extinction to the extinction coefficient), the edge effect contribution is expected to be reduced or even vanished at large size parameters (about hundred or higher). If it is necessary to study most thoroughly the features of the optical characteristics and there is no need to average these values over some microphysical parameters of the medium, then exact methods, taking into account the edge effect, have the undisputed advantage [17,18].

In this study, we primarily perform the numerical calculations of optical characteristics at size parameters exceeding about hundred. The used techniques are reliable, and our results do not reveal significant differences with respect to the calculations that take into account the edge effect [17]. Many features of the transformed field are smoothed out in passage from a single particle to particle ensemble. The particle size distribution parameters affect the corresponding optical characteristics. In this paper, we focus on a numerical study of the scattering coefficient in the forward direction and the extinction characteristics of medium at different particle size distribution parameters for the visible and infrared wavelength regions.

2. Problem formulation

Suppose the electromagnetic radiation is transmitted by a set of preferentially oriented plate crystals. $\tilde{n}=n+i\cdot\chi$ denotes a complex index of refraction of a crystal. Let a be the side length of a base of a hexagonal plate (or a radius of a plate base), and d be the plate thickness. The law of crystallographic growth dictates that the plate diameter and the thickness are related by $d=2.020\cdot(2\cdot a)^{0.449}$ [19]. This relation is valid, leading to the simplification of the numerical calculations of optical characteristics for particle ensemble. It is convenient to introduce the positions of the source, the receiver, and the plane of preferred crystal orientation with respect to the laboratory coordinate system by an appropriate angle couple (ϑ_i,φ_i) $(i=1,\ 2,\ 3)$ of spherical coordinate system (see Appendix). Also, the orientation of a particle with respect to the Cartesian coordinate system is specified by Euler angles. We define the three Euler angles of rotation α, β, γ as a combination of the quantities (ϑ_1,φ_1) and $(\vartheta_3,\ \varphi_3)$ (these angles connect the laboratory coordinate system with the incident radiation and the scatterer accordingly). The angle α defines the rotation of the scatterer perpendicular to the basal face of the plate. Obviously, for a hexagonal plate, all α-dependent quantities have a period of 60°. The direction of propagation of an elliptical polarized plane wave with respect to the normal of the plate base is specified by the angle β, and the angle γ specifies the orientation of the polarization plane. This numerical experiment was schematically described in our work [12]. The particle size distribution is defined as the modified gamma distribution [4]

$$N(a)=C\frac{\mu^{\mu+1}}{G(\mu+1)}\frac{1}{a_m}\left(\frac{a}{a_m}\right)^{\mu}\exp\left(\frac{-\mu a}{a_m}\right). \tag{1}$$

This function adequately describes the size spectrum of the atmospheric ice crystal system. In Eq. (1), C is the number of particles in the volume element; a_m is the plate radius, corresponding to the maximum of the function $N(a)$; μ is a dimensionless parameter, which characterizes the steepness of slopes at the maximum of $N(a)$; and $G(\mu+1)$ is the gamma function. Eq. (1) can be used to describe the properties of crystals in clouds by taking into account the